SERDP Tin Whisker Testing and Modeling: Whisker Geometric Risk Model Development

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Whisker group discussion Dec. 3, 2014

Tin Whiskers

- Electrical short circuits
  - Intermittent if current is more than 10s of mA
  - Permanent if current is less than 10s of mA
  - Found recently in accelerator pedal position sensor (H. Leidecker, L. Panashchenko, J. Brusse, “Electrical Failure of an Accelerator Pedal Position Sensor Caused by a Tin Whisker and Investigative Techniques Used for Whisker Detection” [1])
- Debris/Contamination
  - Short circuits
  - Interferes with optical paths and MEMS
- Metal Vapor Arc
  - Whisker shorts can vaporize into a conductive plasma able to conduct hundreds of amps
  - http://www.calce.umd.edu/tin-whiskers/mva50V70torr.html

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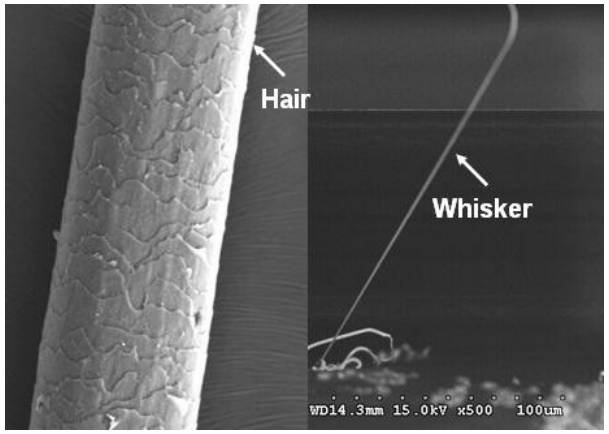
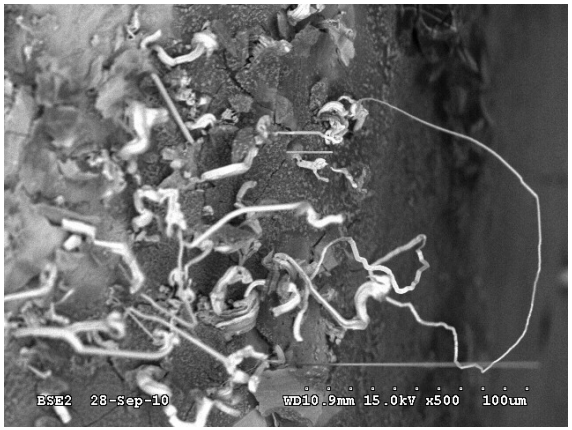
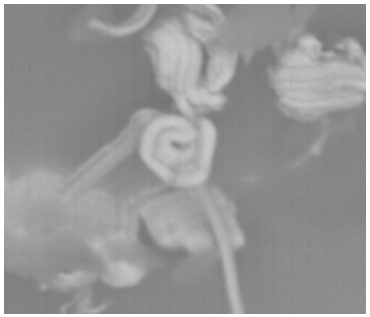
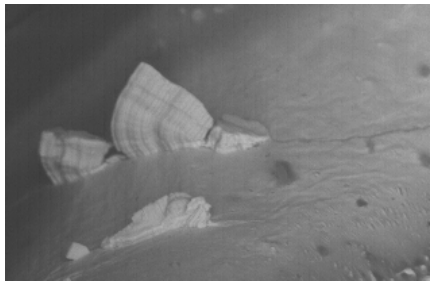
Whiskers: Description

- Metals that grow whiskers include
  - Tin, Zinc, Cadmium
- Metallic whiskers are crystalline filamentary structures
- Grow outward from metal surfaces
- More commonly found in electrodeposited Sn coating and Sn based alloys
- Shape
  - Filaments
    - Straight
    - Kinked
    - Spiral
  - Nodules
  - Odd-shaped eruptions
- Typical length strongly dependent upon circumstances
  - No whiskers, 10 µm, 500 µm, 1 mm, 10 mm, 25 mm
- Typical thickness – 0.5 to 50 microns
- Whisker density varies greatly – no whiskers to over 1000 mm^2









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SERDP WP1753 Technical objective

- **Perform systematic tin-whisker testing to improve the reliability of military electronics**
  - **Provide an understanding of the key design, manufacturing, and environmental variable combinations that can contribute to whisker growth**
  - **Evaluate conformal coating for mitigation effectiveness**
  - **Provide metallurgical analysis of tin whiskers for nucleation and growth-mechanism formulation**
- **Provide an analytical framework to assess functional risk of whiskers to military electronic systems**
  - **Provide a staged approach to risk modeling**
  - **Physical geometry spacing distribution for various lead types**
  - **System function risk assessment through integration of whisker distribution data and circuit details**

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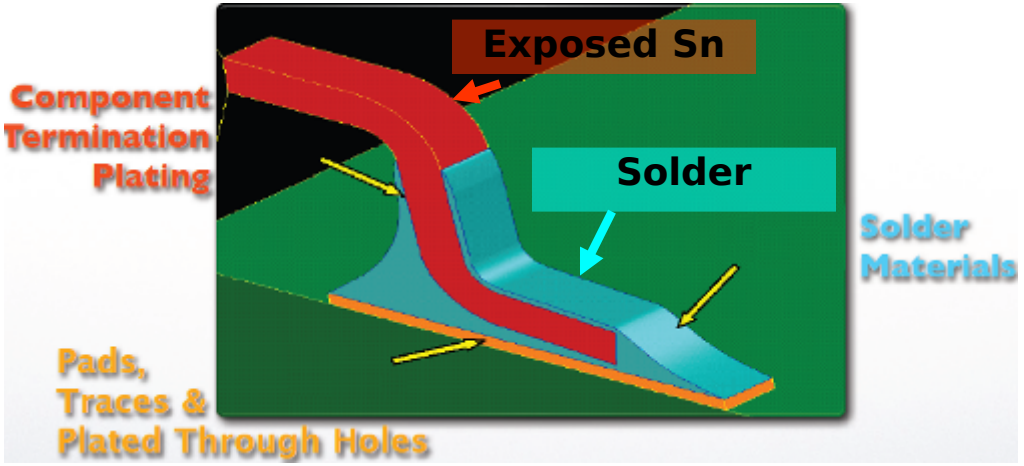
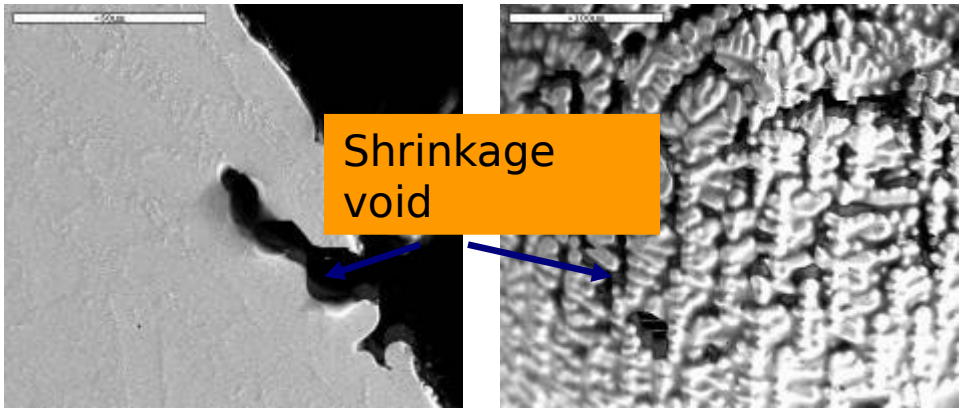
Whiskers in Pb-free solder joints

- No lead(Pb) in electroplated Sn finish – *propensity for whisker formation*
- Poorer wetting – *more exposed Sn plating for same type of components*
- More aggressive fluxes to improve wetting – ionic contamination, oxidation and corrosion *promoting whisker growth*
- Sn-Ag-Cu solder – *what about whisker growth?*
  - Rough surface – trapped contamination, difficult to clean – *higher propensity to whisker*





cross-section top view

Lead-free solder joint roughness, SEM

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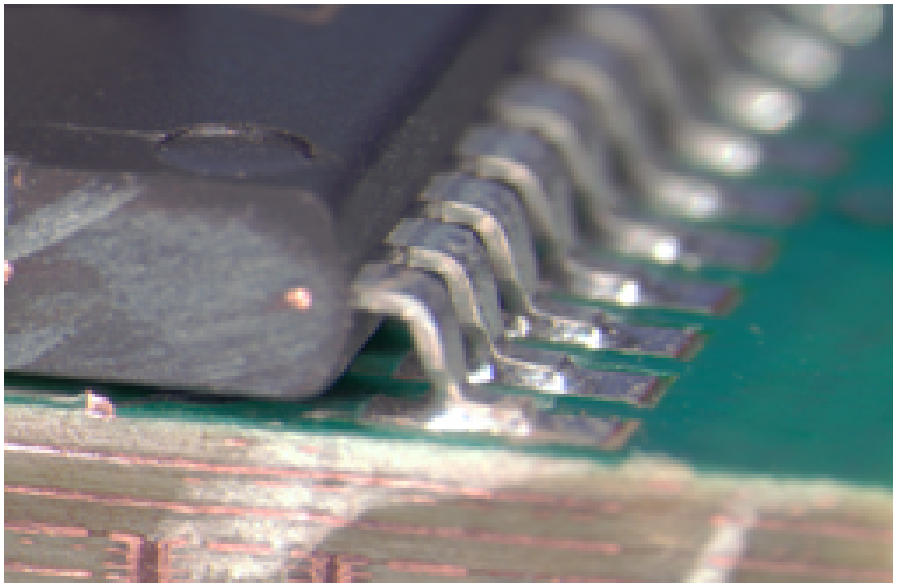
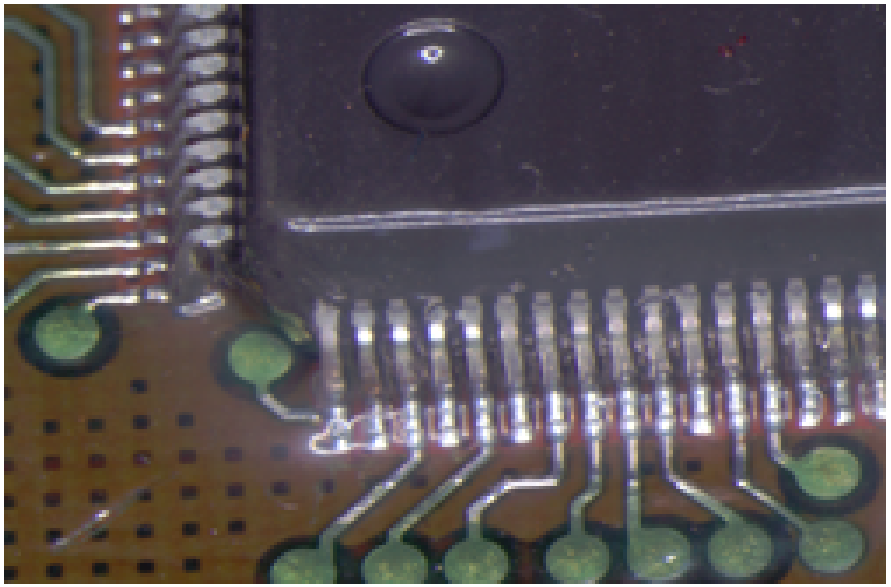
Risk modeling: Gull wing leaded parts



Flat pack (leads on 2 sides)



Quad flat pack (leads on 4 sides)

Note: Users should NOT neglect the concern of LARGE SURFACE AREA structures that may be tin or zinc coated. Things such as connector shells, bus bars, RF shields, fasteners, metal can packages, etc, provide a much larger surface area from which whiskers may form (i.e., greater opportunity for many whiskers). These are often tin or zinc plated and also used in reasonably close proximity to adjacent shorting sites

Gull wing parts have among the closest lead-to-lead gap spacing with large opposing source/target areas

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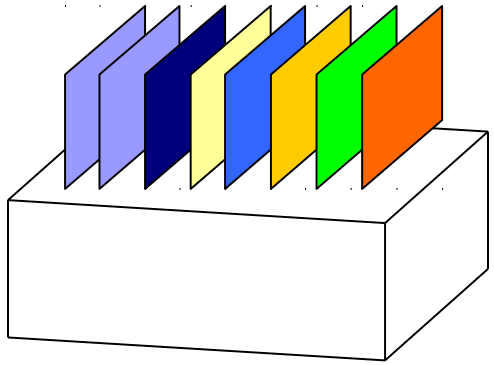
How many leads are there in a box? [3]

One electronic box

Description	# of leads	# of gaps
Analog 1	2009	1787
Power Supply	326	228
Digital 1	2573	2418
CPU	1144	1038
CPU-MEZZ	2512	2478



Risk increases with gap quantity

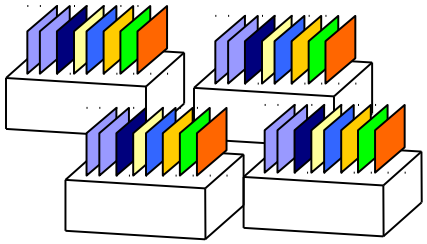
Quad redundant control system

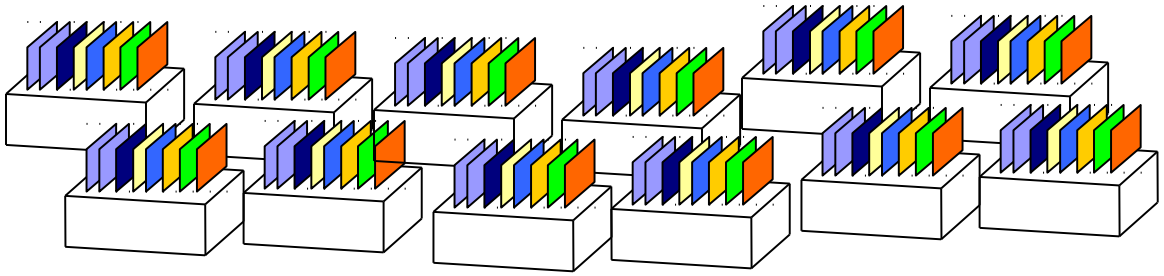
- or -

Vehicles

- or -

Fleets





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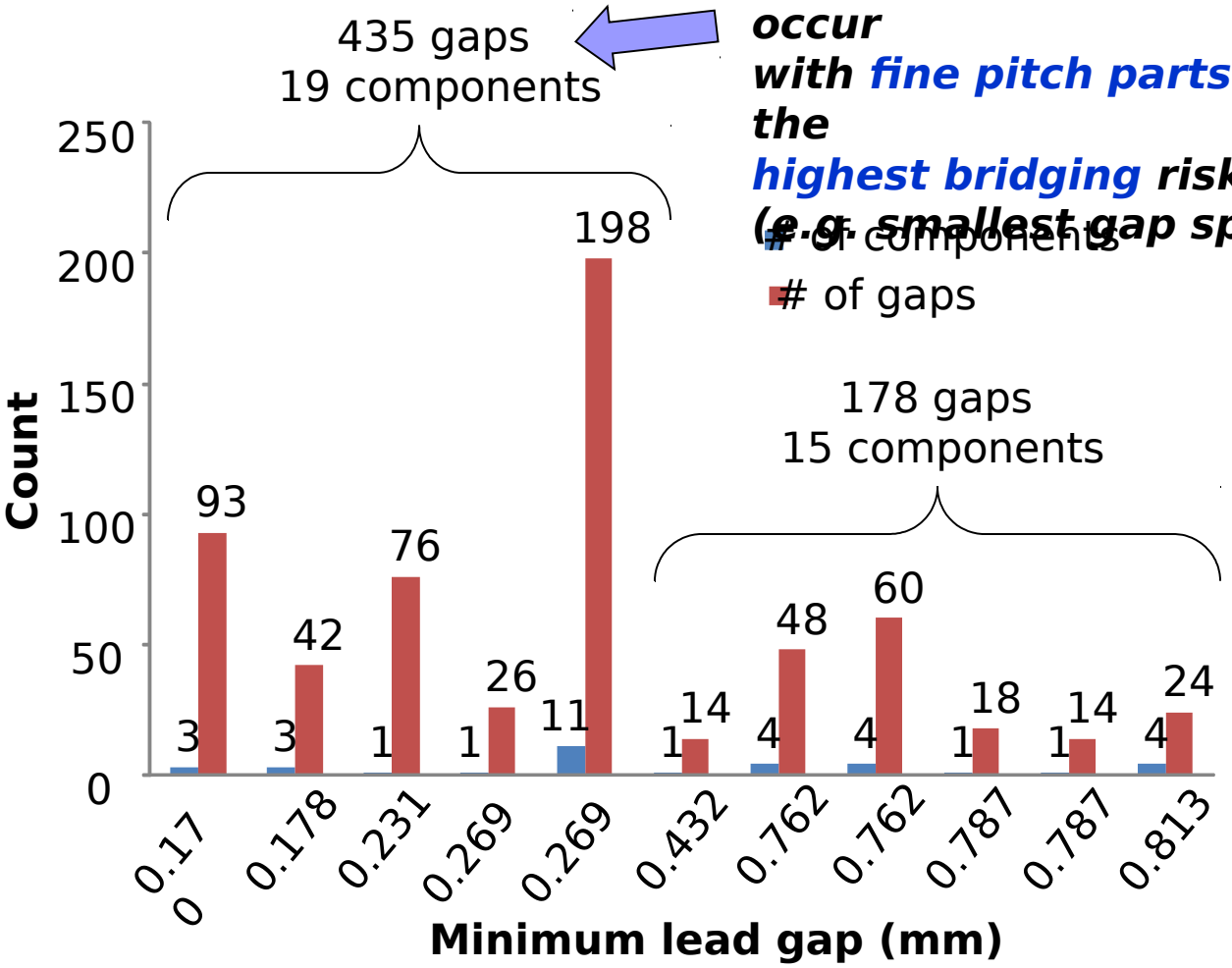
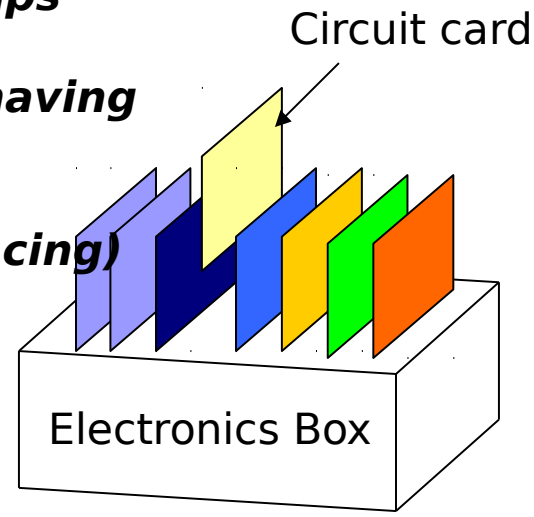
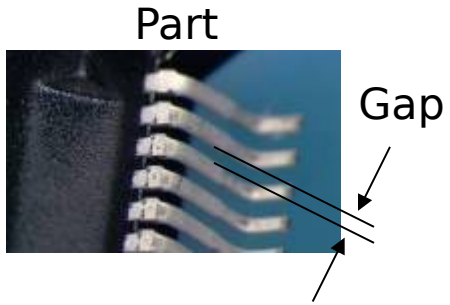
How many gaps are there in a function? [3]

The majority of the gaps occur with fine pitch parts having the highest bridging risk (e.g. smallest gap spacing)







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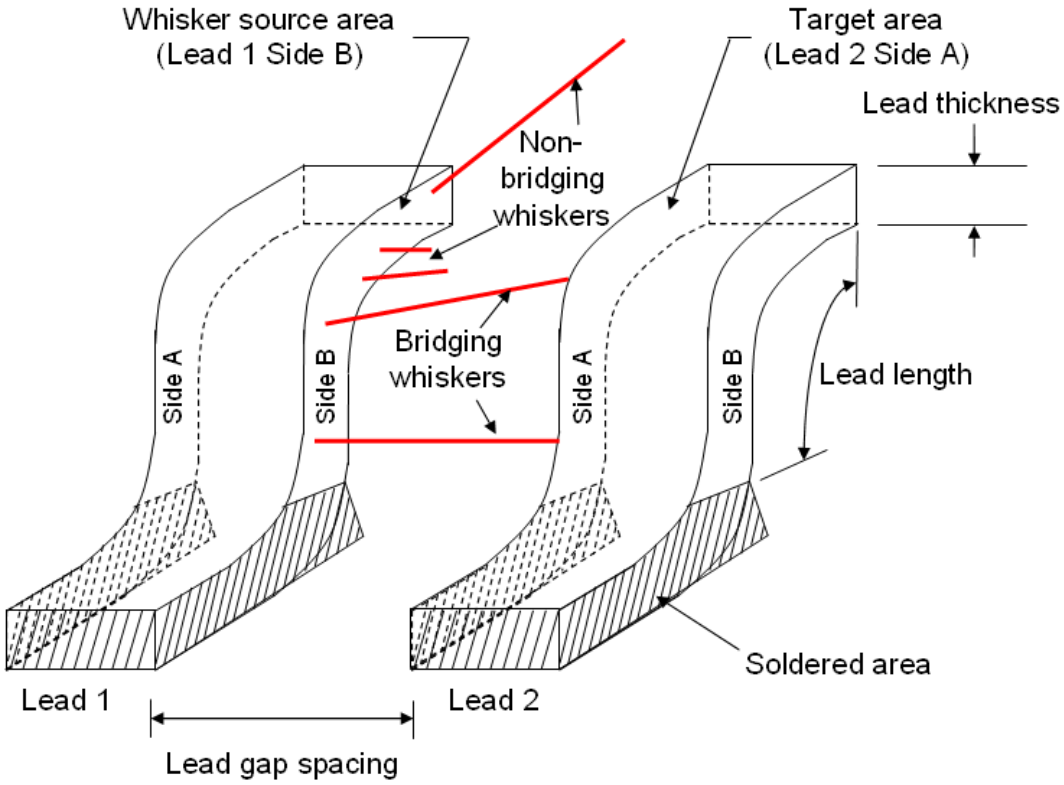
Proximity based whisker bridging risk model



First effort [1]
- 3D to equivalent parallel plate
- One whisker characteristic
- No conformal coat

Current work
- Straight segment 3D
- Lead, solder, pad whisker growth regimes
- Variable area conformal coat
- Multiple part roll-up
- Bridging probability (Monte Carlo)
- Short circuit probability

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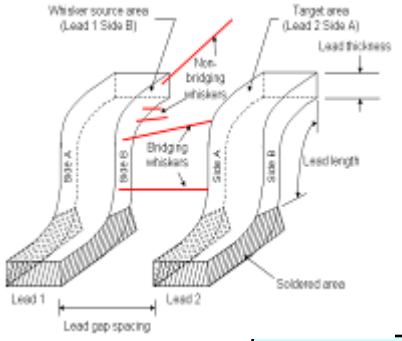
Monte Carlo short circuit modeling approach

Create bridging-risk model for various part types
- Monte Carlo developed lead-to-lead spacing distribution for various lead geometries and whisker angle distributions
- Time-independent model



Conformal coat mitigation
- Adjust whisker length, density, and diameter statistics
- Modify target area based on coverage data
- Modify source area based on "tenting" ability of coating

Information on whiskers: Length, density, diameter, etc.
- Data generated herein
- Published data
- Time and environment captured in whisker length, density, angle and diameter distributions

Evaluate published data on whisker electrical properties [2]

Apply data to a failure modes and effects analysis to determine functional impact

Use model to evaluate bridging risk
- Select representative digital, analog, and power circuits
- Compute total assembly whisker bridging for a give whisker length distribution

Evaluate overall risk of electrical functional impact
- Obtain a probability of each effect

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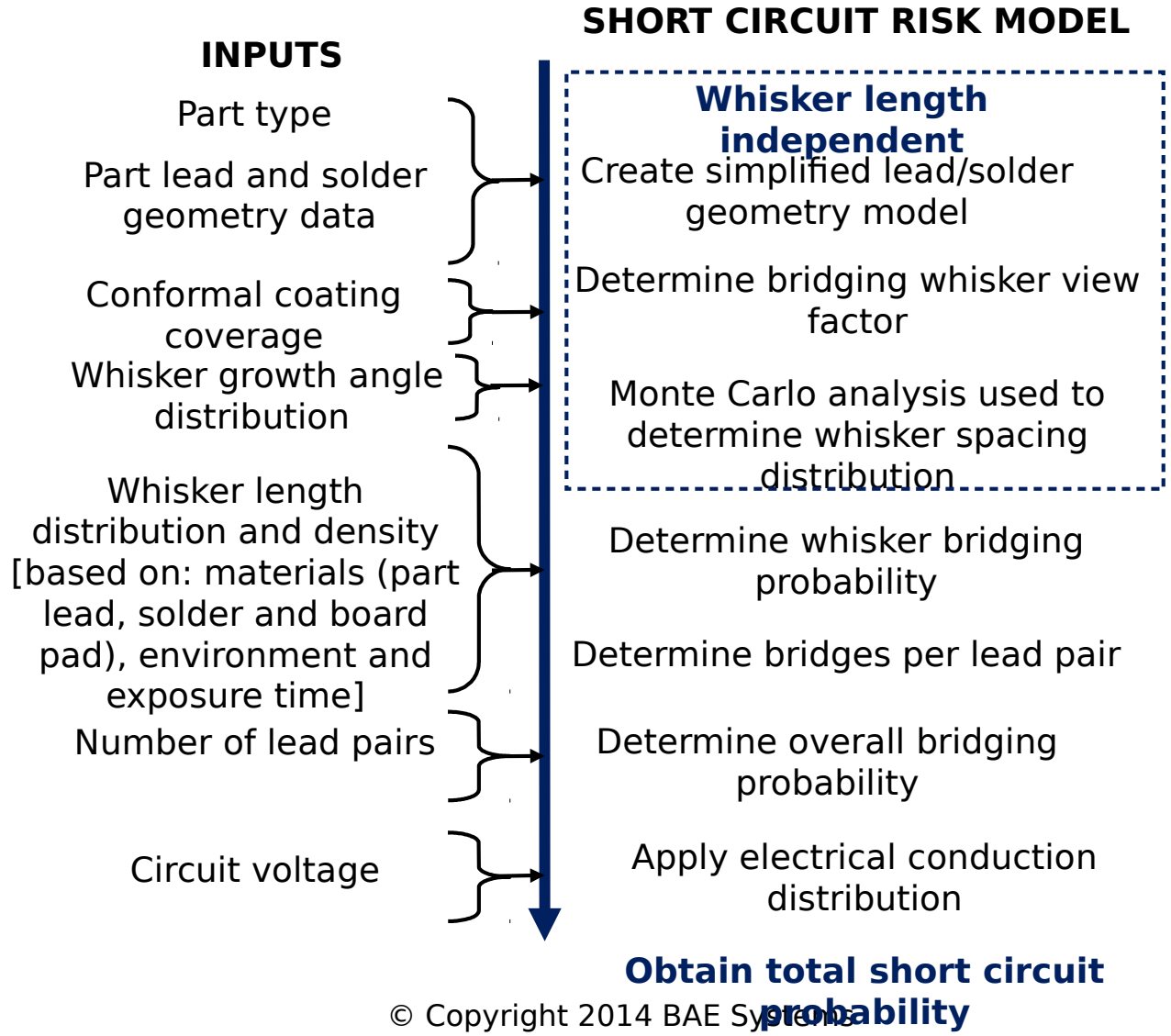
Whisker short circuit modeling approach


SHORT CIRCUIT RISK MODEL
INPUTS
Part type
Part lead and solder geometry data
Conformal coating coverage
Whisker growth angle distribution
Whisker length distribution and density [based on: materials (part lead, solder and board pad), environment and exposure time]
Number of lead pairs
Circuit voltage
Whisker length independent
Create simplified lead/solder geometry model
Determine bridging whisker view factor
Monte Carlo analysis used to determine whisker spacing distribution
Determine whisker bridging probability
Determine bridges per lead pair
Determine overall bridging probability
Apply electrical conduction distribution
Obtain total short circuit probability

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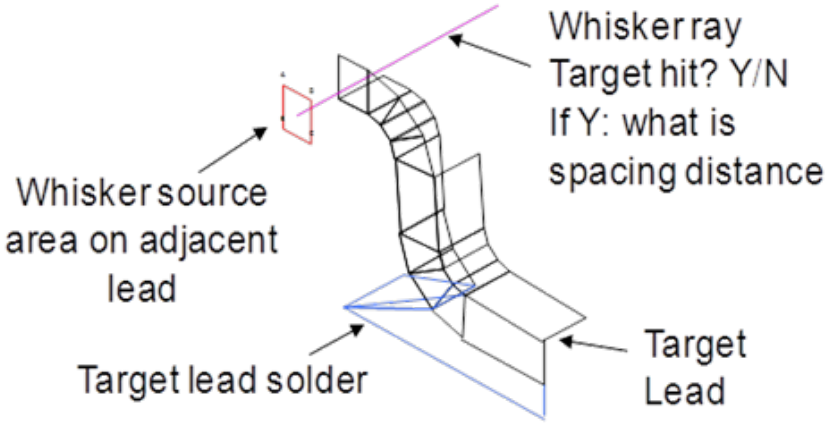
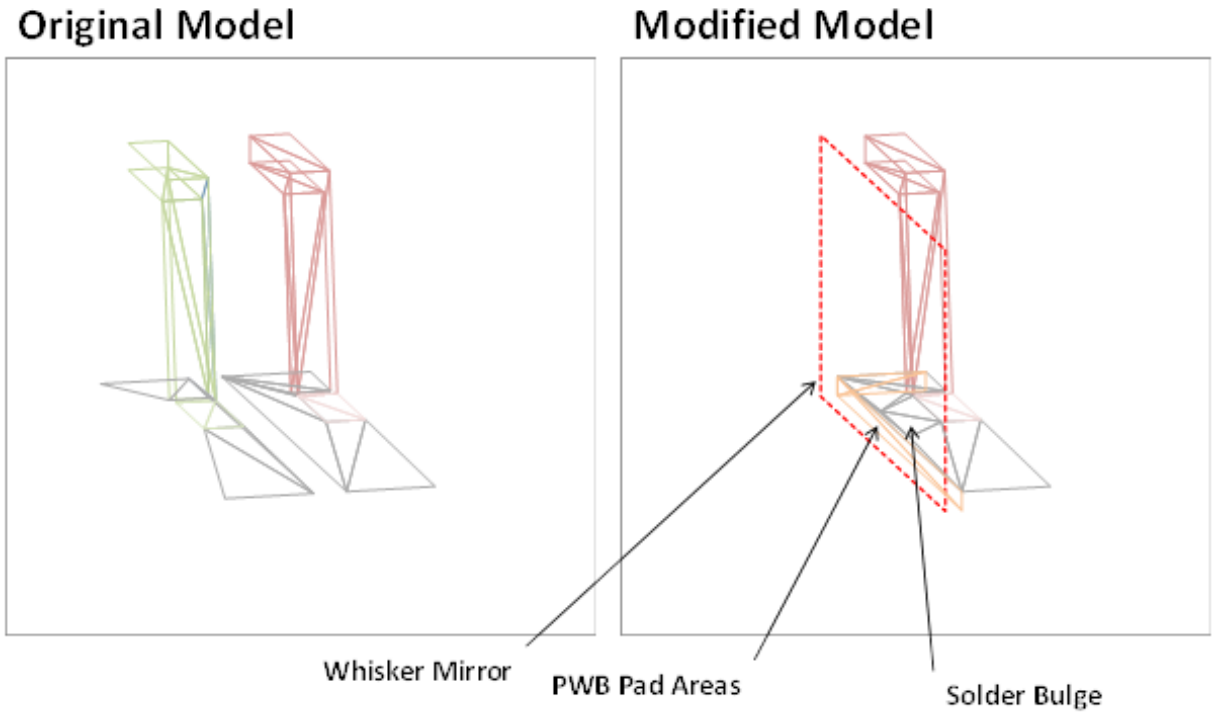
Bridging whiskers

Source whisker “sees” the target
- Will it hit?
- If yes, how long is whisker





Mirror concept reduces geometry related whisker bridging calculation time

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Assumptions

- Conservative
  - Whisker conduction probability is based on gold probe against tin rather than tin-tin contact
- Non-conservative
  - Whiskers from opposite surfaces are not interacting
    - No dueling sabers modeled
    - Whiskers changing azimuth angle during growth and hitting other whiskers is not modelled
  - No electric attraction between whiskers and substrates or between whiskers on adjacent surfaces is modeled
    - Whisker in video is ~ 10 microns in diameter with 50V applied
    - https://nepp.nasa.gov/whisker/experiment/exp4/index.html
      - Smaller diameter whisker would require less voltage to move
      - Longer whisker would be easier to move with a given voltage
    - Electrostatic charge on the insulator ~couple kV charge
    - https://nepp.nasa.gov/whisker/video/Zn-whiskers-HDG-electrostatic-bend.wmv
  - Whiskers are not moving due to air currents
    - https://nepp.nasa.gov/whisker/video/whisker-motion-air.mpg
- Other
  - Metal vapor arcing not considered
    - https://nepp.nasa.gov/whisker/anecdote/2009busbar/index.html

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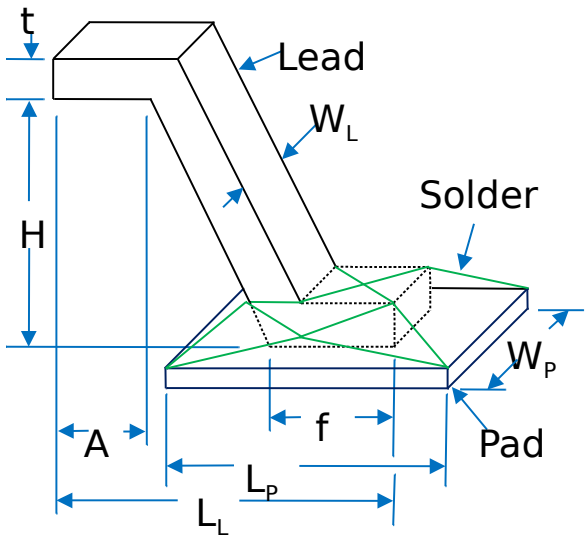
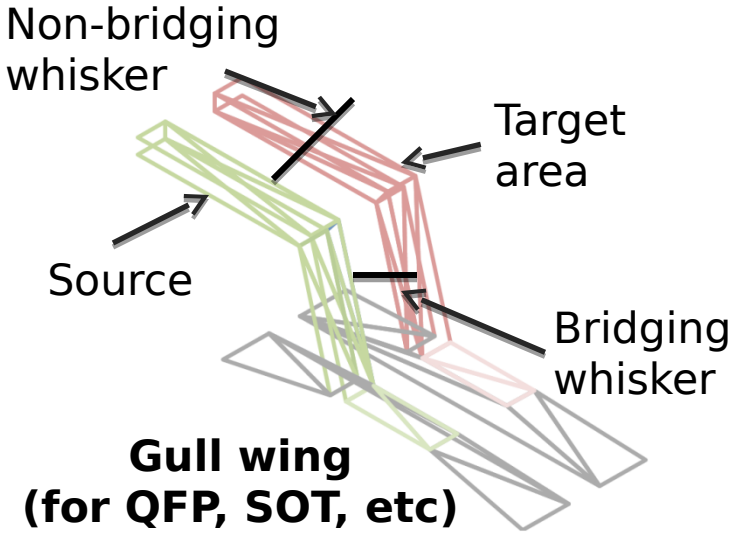
Bridging risk model

Define geometry





Whisker View Factor:

Probability of an infinitely long whisker bridging from either lead

Monte Carlo simulation of whiskers that could bridge from source to target

Input: Source, target and coating geometries and whisker angle and azimuth distributions

Whisker angle and azimuth distributions: Uniform (assumption)

Example: QFP Lead

Generate 1,000,000 infinitely long whiskers on source

View factor
160,000 bridge to target (16%)

840,000 miss

Whisker spacing distribution
Distance from source to target for whiskers that bridge

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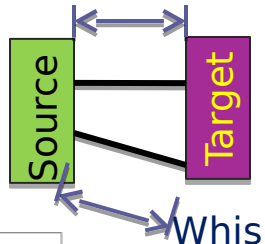
Modeling: Lead spacing and whisker length

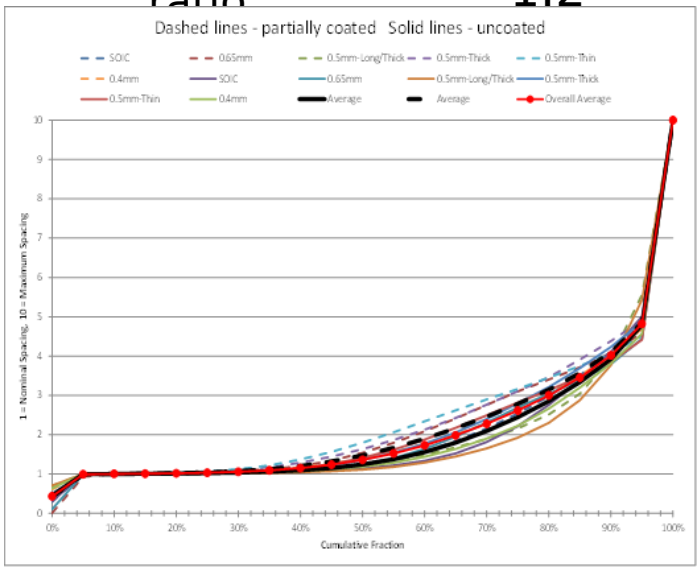
Whisker spacing distributions created for various parts

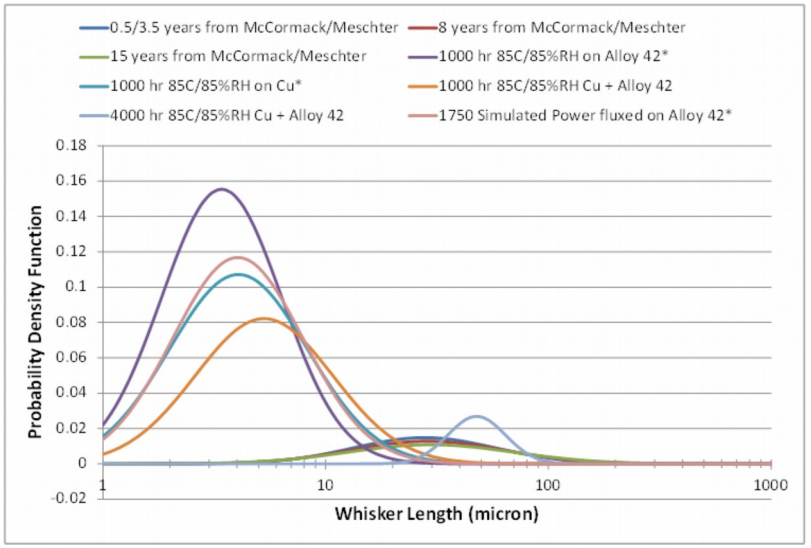
Whisker angle and azimuth distributions: Uniform (assumption)

Ex: Whisker spacing to Nominal spacing ratio = 1 = 1.2



Whisker spacing distribution is a cumulative fraction of bridgeable spacing distances relative to nominal spacing




0.5/3.5 years from McCormack/Meschter
8 years from McCormack/Meschter
15 years from McCormack/Meschter
1000 hr 85C/85%RH on Alloy 42*
1000 hr 85C/85%RH on Cu*
1000 hr 85C/85%RH Cu + Alloy 42
4000 hr 85C/85%RH Cu + Alloy 42
1750 Simulated Power fluxed on Alloy 42*
Probability Density Function
Whisker Length (micron)

Lead whisker spacing distribution
(Also done for solder and pad)

Whisker length distribution

Cross correlation of distributions gives whisker bridging probability

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Modeling: Overall short circuits

1) Whiskers per lead = Whiskerable area x Whisker density

2) Bridges per lead pair = whiskers per lead x whisker view factor (having coating adjustments) x whisker bridging probability

3) Bridges per assembly = Bridges per lead pair x Number of parts x Number of lead spaces

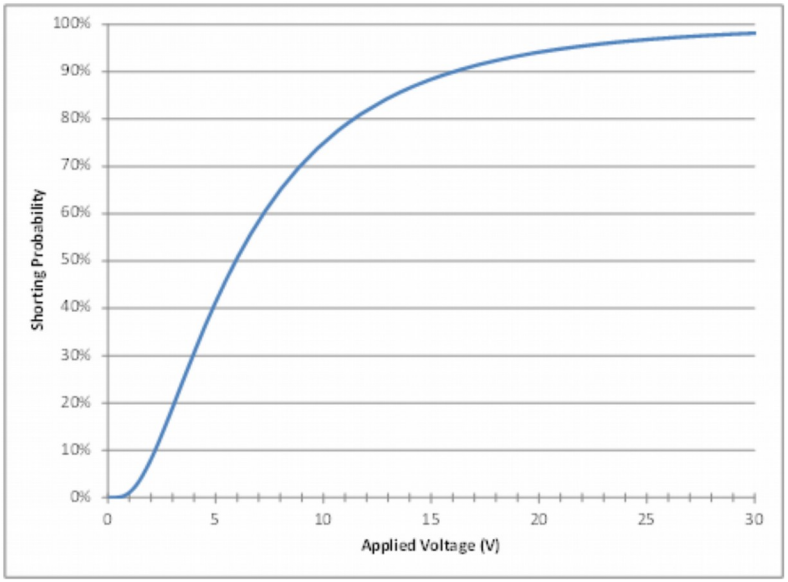
4) Short circuits per assembly = Bridges per assembly + Voltage+ Voltage shorting probability

Whiskerable area for various parts

Whisker Origin:	Lead	Solder
Part Type	Whiskerable Area (mm^2)	
MSOP	0.64	0.67
PQFP	0.63	0.49
QFP	5.68	3.63
SOIC	1.32	1.20
SOIC+	3.09	1.81
SOT	1.26	1.19
SSOP	1.34	0.89
TQFP	0.72	0.52
TSSOP	0.62	0.55
J-side	4.76	2.28
J-corner	1.05	2.18

SOIC+ is an SOIC geometry with a stepped lead width

Shorting probability versus applied voltage



(Courey [5])

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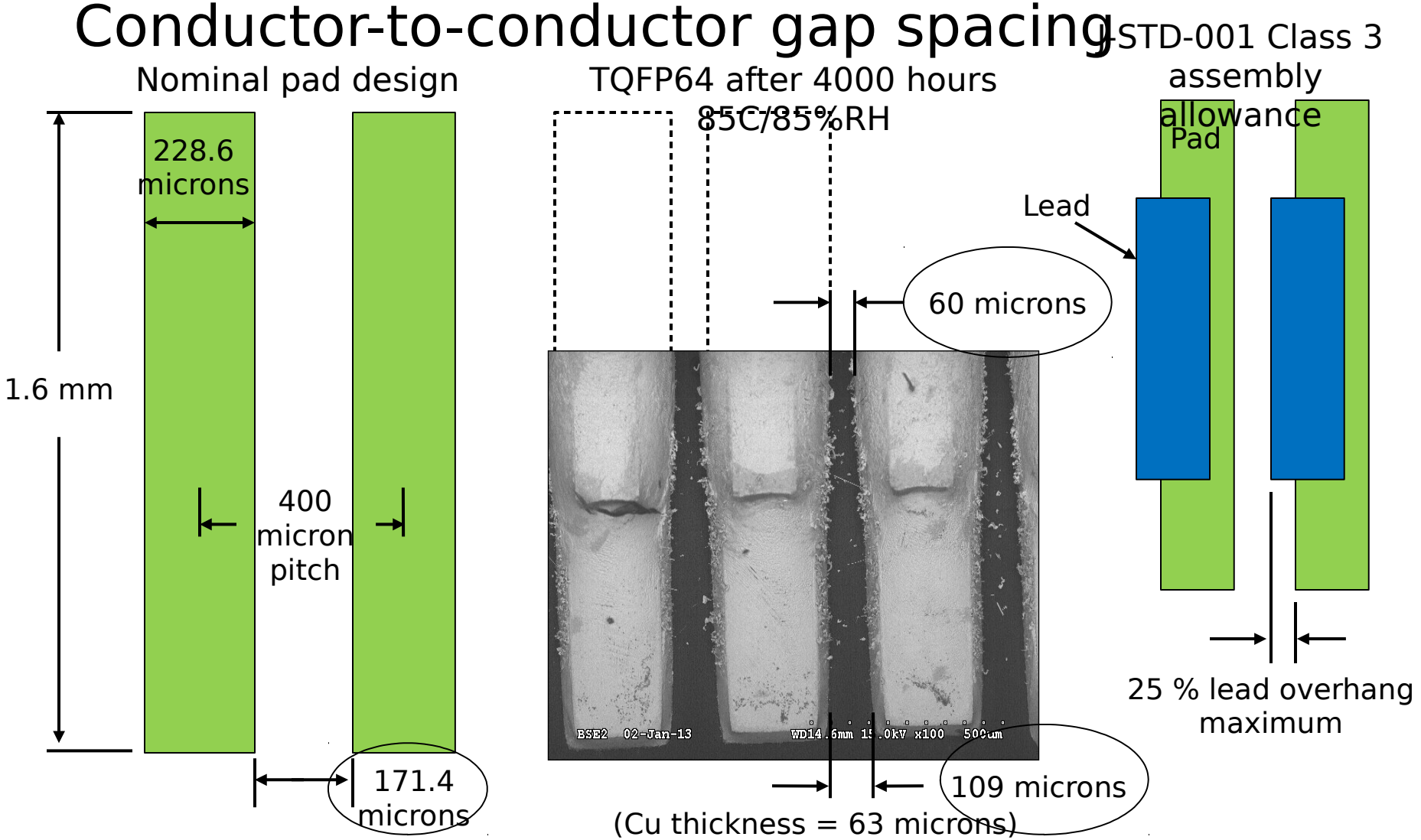
Real life considerations: Conductor-to-conductor gap spacing



Gap spacing reduction by board fabrication etch tolerances, lead misalignment, and a bulbous solder joint

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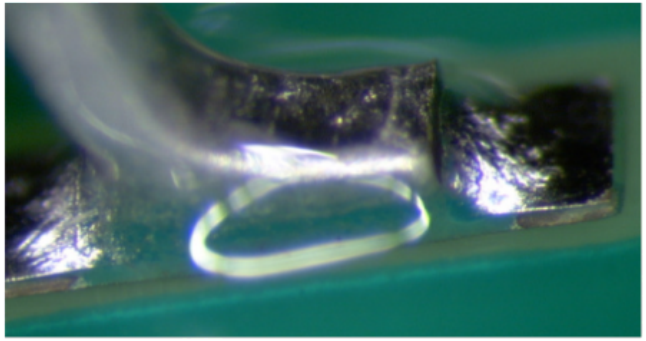
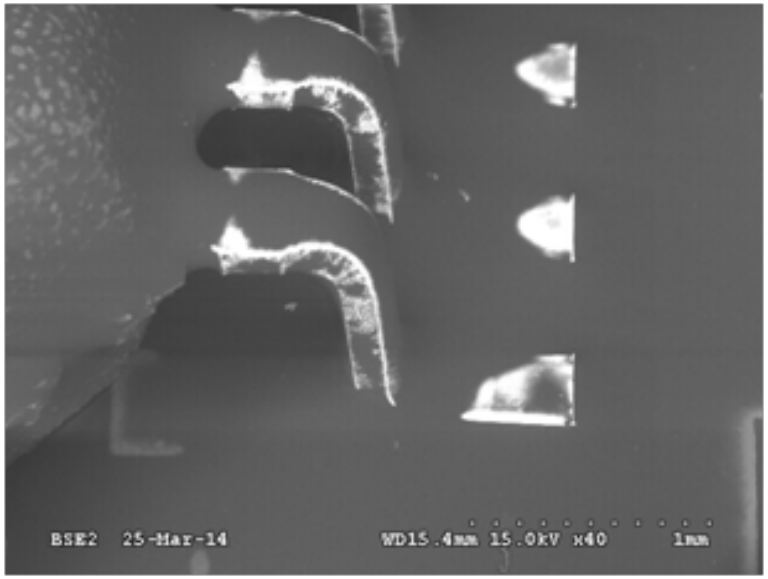
Real life considerations:
Conformal coating coverage

Conformal coating coverage assessment of low VOC spray coating



Optical image



Isometric SEM image

- The white color in the SEM images indicates that the coating thickness is less than three microns
- No coating behind the lead
- 90% front, 50% side and 0% back
    - = 40% uniform coating model value

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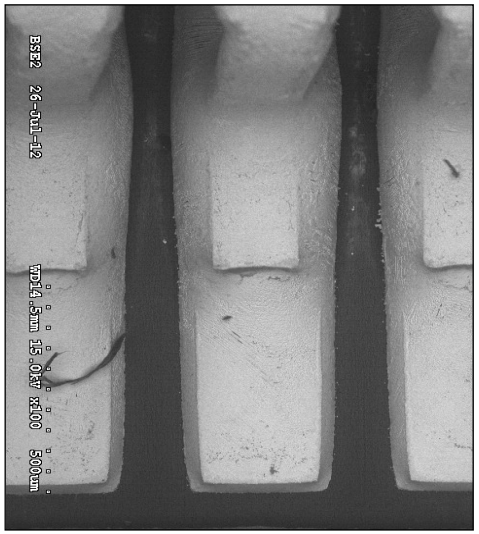
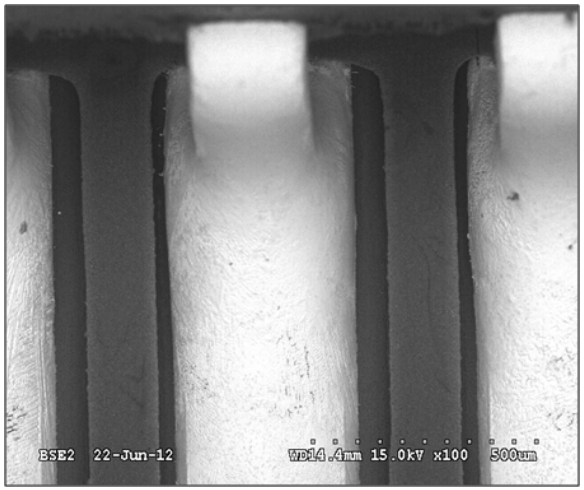
SERDP 85 ▼C/85RH HTHH 1,000 vs. 4,000 hrs [4][5]

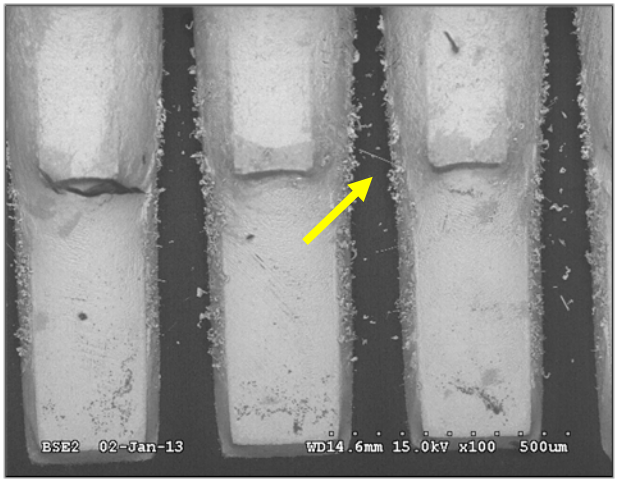
1,000 hours

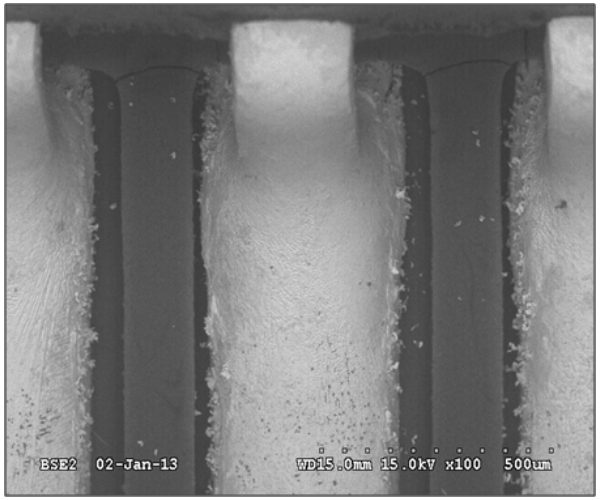




4,000 hours

Significant additional nucleation





Copper alloy lead 64 pin quad flat pack (QFP64 U08, lead 28)

Alloy 42 lead SOT6 with a 0-0 (U65, lead 4)

0-0 contamination

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Whisker parameters:
Length reference distributions

Tin source	Thickness (microns)	Substrate	Environmental exposure	Maximum observed whisker length (microns)	Lognormal μ (ln mm)	Lognormal σ	Density (whiskers /mm²)
SAC305 Solder [4][5]	3 to 25	Copper board pads (clean parts and board)	1,000 hours 85°C/85 %RH	76	-4.978	0.710	297 to 1,454 (4,000 hr level)
	3 to 25	Copper board pads (contaminated parts and board)		186 (Note 1)	-4.795	0.6962	
Plated Sn [6]	5 to 9	Copper C194	2.5 years room, 1,000 cycles -55 to 85°C, 2 months 60°C/85%RH	39	-4.571	0.9866	2,192 to 3,956
	7 to 9	Nickel plating over Copper C194		greater than 200 (Note 1)	-4.306	0.8106	126 to 3,573
Plated Sn Dunn [7] evaluated in [8]	5	Copper plated brass (specimen 11)	15.5 years: 3.5 years room temp. and humidity, 12 years in a dessicator with dry room air	1,000 maximum specimen 11 length	-2.651	0.9212	Not available
				733, average of specimen 11 maximum lengths at various locations	-2.783	0.8592	

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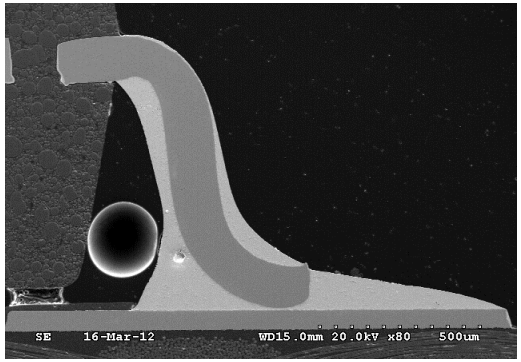
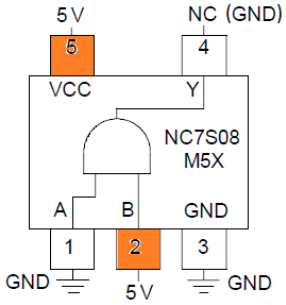
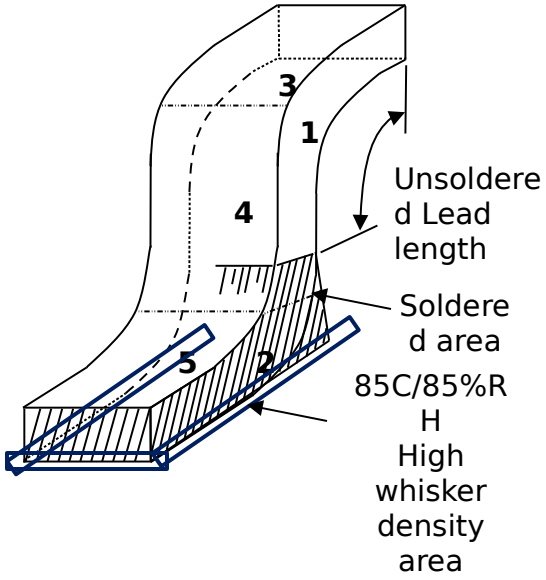
Whisker parameters: Density

Whisker count for SOT5 at 0-0 Cleanliness level 4,000 hr 85 ➤C/85RH







	Whiskers per board pad	Whisker density (whiskers/mm²)
Minimum	58	297
Maximum	284	1454
Average	182.8	936

	Whiskers per lead on the side	Whisker density (whiskers/mm²)
Minimum	0	0
Maximum	44	236
Average	12.9	69

Maximum whisker density at the pad edge is 1454 whiskers/mm2

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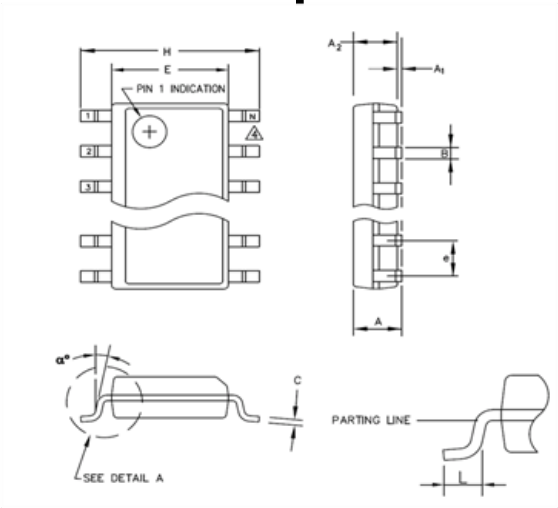
Example: Geometry inputs



Part Drawing Dimensions (mm):	
Package Height (A_2) =	1.4
Package Seating Plane (A_1) =	0.1
Lead Span (H) =	16
Body Width (E) =	14
Lead Foot Length (L) =	0.6
Lead Thickness (c) =	0.145
Lead Width (B) =	0.18
Lead Pitch (e) =	0.4
Lead Angle From Vertical (α deg) =	0
Number of Leads =	128
Number of Sides with Leads	

128 TQFP

Default parameters

PWB Pad Length over Lead Foot Length (mm) =	1.04
PWB Pad Width over Lead Width (mm) =	0.111
Fraction for Minimum Whisker Length Plot (Note 1)=	5.00%
Fraction for Maximum Whisker Length Plot (Note 1) =	90.00%
Use Geometric Mean for Midpoints (Note 2)=	TRUE
Lead Exit Fraction (*) (of package height) (Note 3) =	50%
Minimum First Bend Distance (*) (mm) =	0.1
Pad Spacing Reduction from Solder Bulge (mm) (Note 4) =	0.049
Relative Height of Bulge (Note 4) =	50%
Rounding Digits for Prompt Display =	4

Calculated parameters

Lead Spacing (mm) =	0.22
Solder Spacing (mm) =	0.06
Pad Spacing (mm) =	0.109
Lead Thickness/Spacing (non-dim) =	0.659
Lead Thickness/Solder Spacing (non-dim) =	2.417
Lead Thickness/Pad Spacing (non-dim) =	1.330
Lead View Factor Metric (non-dim) =	0.260
Solder View Factor Metric (non-dim) =	0.456
Pad View Factor Metric (non-dim) =	1.618

Example: Whisker parameter inputs

Lead

Lead Whisker Distribution (fill in green highlighted cells as appropriate):	
Distribution =	2
Whisker Density (whiskers/mm²) =	**69**
Whiskerable Area =	1.460
Total Whiskers Generated =	100.7
Whisker Bridging Fraction =	0.00%
Whisker View Factor =	0.101
Coating Effectiveness =	0%
Total Whiskers Bridging =	**8.518E-11**
3-Parameter Lognormal Distribution:	
Whisker Minimum (0) =	
Whisker μ (location, ln(mm), -1.8965) =	-4.795
Whisker σ (scale,nondim, 1.5169) =	0.6962

Solder

Solder Whisker Distribution (fill in green highlighted cells as appropriate):	
Distribution =	2
Whisker Density =	**936**
Whiskerable Area =	0.533
Total Whiskers Generated =	498.6
Whisker Bridging Fraction =	0.01%
Whisker View Factor =	0.2485
Coating Effectiveness =	0%
Total Whiskers Bridging =	**0.01149**
3-Parameter Lognormal Distribution:	
Whisker Minimum (0) =	
Whisker μ (location,ln(mm), -1.8965) =	-4.795
Whisker σ (scale,nondim, 1.5169) =	0.6962

Pad

Pad Whisker Distribution (fill in green highlighted cells as appropriate):	
Distribution =	2
Whisker Density =	**936**
Whiskerable Area =	0.311
Total Whiskers Generated =	291.0
Whisker Bridging Fraction =	0.00%
Whisker View Factor =	0.311
Coating Effectiveness =	0%
Total Whiskers Bridging =	**0.003275**
3-Parameter Lognormal Distribution:	
Whisker Minimum (0) =	
Whisker μ (location,ln(mm), -1.8965) =	-4.795
Whisker σ (scale,nondim, 1.5169) =	0.6962

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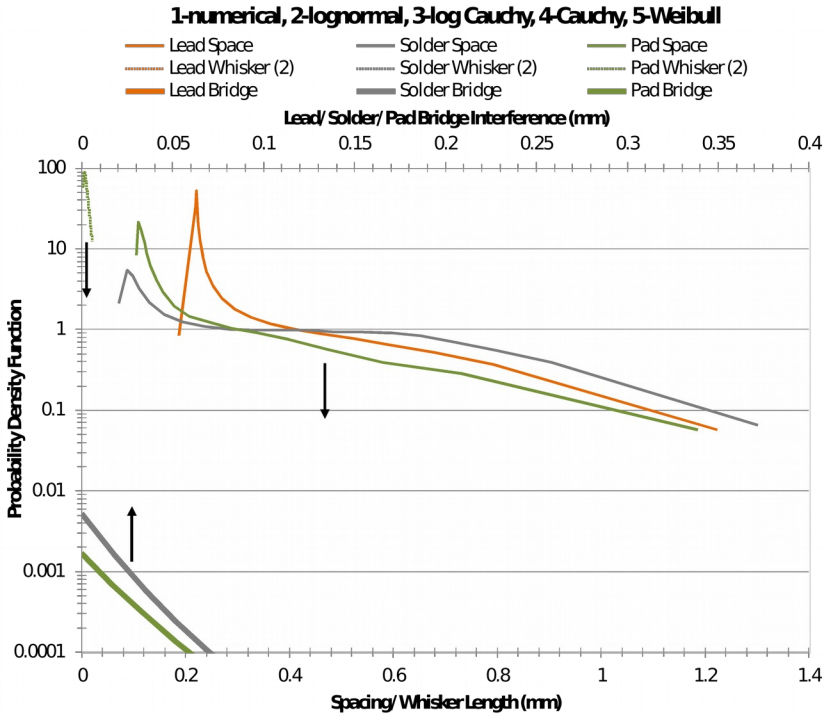
Example: Whisker shorting results

TQFP128 SAC305 soldered with no conformal coating
Applied voltage of 5 volts
Whiskers: 1,000 hour 85C/85%RH exposure with mildly contaminated parts and boards; lognormal μ = -4.795 ln(mm) and σ = 0.6962



Total lead spaces =	124		
Applied Voltage =	**5**	**V**	
Shorting Probability =	41.4%		
Whisker Type:	**Lead**	**Solder**	**Pad**
Bridges per lead:	6.24E-06	0.0115	0.003275
Bridges per part:	0.000774	1.425	0.406
Shorts per part:	0.00032	0.589	0.168
TOTAL SHORTS =	**0.7577**		

2 x 0.7577 = 1.5154

With two TQFP128 parts a short circuit failure is expected

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Example: Whisker shorting results

TQFP128 SAC305 soldered with no conformal coating
Applied voltage of 5 volts
Whiskers: 1,000 hour 85C/85%RH exposure with mildly contaminated parts and boards;
lognormal μ = -4.7

TOTAL SHORTS =	0.7577

Change cleanliness:
1,000 hour 85C/85%RH exposure with **clean parts and boards**; lognormal μ = -4.978 ln(mm) and σ = 0.710

TOTAL SHORTS =	0.373

Add coating:
40 percent conformal coating co

TOTAL SHORTS =	0.2486

Reduce shorts by 1/3

Change solder, remove coating:
TQFP128 **tin-lead** soldered with **no conformal coating** Applied voltage of five volts (1,000 hour 85C/85%RH exposure with clean parts and boards; lognormal μ = -4.978 ln(mm) and σ = 0.710).

TOTAL SHORTS =	0.00014

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Summary

- Provides a means of comparing various
  - Coating and tin-lead solder mitigations
  - Component geometry types
- The partitioning of the calculation between the geometry and the whisker distribution allows rapid recalculation of short circuit risk as new whisker distributions become available.

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